

RESEARCH

# Industrial-scale purging of ammonia by using nitrogen before environmental discharge

Ahmet Ozan Gezerman<sup>1</sup>

Received: 30 September 2015 / Accepted: 23 August 2016 / Published online: 8 September 2016  
© The Author(s) 2016. This article is published with open access at Springerlink.com

**Abstract** For efficient discharge and storage of refrigerated chemicals such as ammonia, special processes must be developed, and several related parameters must be checked and evaluated. In this study, pressure changes in ammonia storage systems that are purged by nitrogen gas, during filling by gaseous ammonia, were calculated and an environment-friendly technique for discharging ammonia gas was developed. In addition, exergy analysis for the system was performed, and the nitrogen discharge rate in the system was calculated. The total exergy loss was determined to be 43.18 %, and the nitrogen discharge rate was determined to be 38,995 dm<sup>3</sup> h<sup>-1</sup> for the proposed system.

**Keywords** Purging · Ammonia · Nitrogen · Cryogenic · Multistage compressor

## List of symbols

$e_{cp}$	Exergy loss in the compressor (kJ kg <sup>-1</sup> )
$e_{cd}$	Exergy loss in the condenser (kJ kg <sup>-1</sup> )
$e_{exp}$	Exergy loss in the expansion valve (kJ kg <sup>-1</sup> )
$e_{pump}$	Exergy loss in the ammonia pump (kJ kg <sup>-1</sup> )
$e_{vessel}$	Exergy loss in the ammonia storage vessel (kJ kg <sup>-1</sup> )
$e$	Total exergy loss of the compression system (%)
$\eta$	Exergy efficiency of the compression system (%)
$s$	Specific entropy (kJ kg <sup>-1</sup> K <sup>-1</sup> )
$T$	Temperature (K)

$T_a$	Ambient temperature (K)
$w$	Compression work per unit refrigerated mass (kJ kmol <sup>-1</sup> )
$\psi_r$	Exergy of reaction at 1 atm, 25 °C (kJ kmol <sup>-1</sup> )
$g_{fi}$	Chemical exergy of a component (kJ kmol <sup>-1</sup> )
$v_i$	Volume fraction (cm <sup>3</sup> cm <sup>-3</sup> )
$n$	Mole fraction (mole mole <sup>-1</sup> )
$T_{cd}$	Temperature in the condenser (K)
$T_{cp}$	Temperature in the multistage compressor (K)
$T_{exp}$	Temperature in the expansion valve (K)
$T_{pump}$	Temperature in the ammonia pump (K)

## Introduction

For storing refrigerated gasses like ammonia, maintenance of systems in which these gasses are used is very important. Since ammonia is a pungent, cryogenic, and corrosive refrigerated liquid, several problems are encountered in systems in which it is used. For example, ammonia has a low boiling point (−33 °C), so the process lines should be able to prevent temperature variations. Therefore, special methods are needed to purge ammonia from the process lines. Based on this demand, Shi et al. [1] designed a purging tower and investigated the tower's performance in ammonia storage systems.

In addition, a different method was investigated by Oberski et al. [2], where ammonia gas was used as a reductant to purge the system.

Another patented approach toward purging ammonia during the storage process was demonstrated by Ishizaka et al. [3]. Here, titanium tetrachloride was used as the inert material, but this process has not been implemented on an industrial scale. Another investigation on the purging of

✉ Ahmet Ozan Gezerman  
ahmet\_ozan@yahoo.com;  
ahmetozangezerman78@hotmail.com

<sup>1</sup> Department of Chemical Engineering, Faculty of Chemical and Metallurgical Engineering, Yildiz Technical University, Istanbul, Turkey



refrigerated chemicals such as ammonia from process lines was performed by Shaikh et al. [4]. In this work, air was used to purge the ammonia from the storage system. However, the air was introduced into the system by a device that increased the operation cost. Further, Sun et al. investigated the purging of refrigerated and cryogenic materials from process lines [5]. In these studies, ammonia was treated using urea, which was introduced by a dosing system.

Another investigation of an ammonia storage system and its periodic maintenance was performed by Mayer et al. [6], and this work is useful because it tackled purging on an industrial scale.

There are several experimental works on the application of ammonia storage systems. Le Lostec et al. [7] reported promising experimental-scale results for an ammonia–water absorption chiller system.

Wright [8] also developed a patent for the storage of refrigerated materials and purging of the systems; however, the operation cost is high. Other methods have also been designed based on computational fluid dynamics (CFD) for safe purging of the pipelines of refrigerated systems [9]. Maekawa [10] applied another method for purging ammonia storage systems, using fluorine as the cleaning gas. Another gas-purging application is a refrigeration cycle system, developed by Dincer and Kanoglu [11].

Ammonia, which is the main chemical considered in the present work, is widely used in several industries. In processes involving ammonia, appropriate methods of discharge are imperative for long-term maintenance of the process equipment and production/compressor lines. Hence, purging is indispensable, and for this purpose, the physical form of ammonia must be controlled. Ammonia is generally used in anhydrous form (99.9 %) in industrial processes. However, because of its pungent odor, ammonia stored at cryogenic temperatures should not be discharged into the environment in anhydrous form.

In the present work, I propose that during ammonia storage, the empty tank should be first filled with ammonia gas and then with liquid ammonia. During the filling operation, the main objective is to condition the tank to afford an ambient storage environment for liquid ammonia. During the operation, the liquid anhydrous ammonia storage tank is partially filled (i.e., only three-fourth of the tank is filled), and the unfilled portion is used to accommodate gasified ammonia. A part of this gasified ammonia is used for conditioning the other empty tank, while the rest is sent to the multistage compressor for liquefaction, in order to maintain the level of liquid in the liquid ammonia storage tank. During the operation, the gaseous ammonia obtained from liquid ammonia is compressed and then liquefied

by the multistage compressor. This approach helps in mitigating thermodynamic losses, as confirmed by a thermodynamic assessment of the proposed process based on exergy analysis.

## System description and calculations

For increasing ammonia gas concentrations in the tank, the compressor suction valve of tank B is slowly opened. The purpose of this action is to purge nitrogen gas into tank B, by taking the ammonia gas from tank A, so that the ammonia gas concentration in tank B is increased and nitrogen gas is discharged. Ammonia gas from tank A reaches tank B through the shortest possible route in the pipeline. With increasing ammonia concentration in tank B, the pressure on the nitrogen gas mixture increases, and hence, nitrogen is forced out of the tank (Fig. 1).

Tank A is filled with liquid ammonia, and tank B is filled with nitrogen gas. The purpose of this arrangement is to purge nitrogen gas in tank B, in preparation for filling with liquid ammonia. Because of the ambient temperature, the liquid ammonia in tank A (1 atm,  $-33\text{ }^{\circ}\text{C}$ ) may vaporize and reach the compressor suction by pipeline 1. The liquefied ammonia is repeatedly directed to tank A from the compressor discharge via pipelines 2–5. The conditioning work involving prefilling tank B with liquid ammonia, by using pipeline 1, was accomplished by the vaporized ammonia in tank A.

The changes in pressure with time during the purging of ammonia gas using nitrogen gas are shown in Fig. 2. The green line denotes the pressure change depending on ammonia gas concentration during 8 h; the blue line indicates the pressure change of nitrogen gas in 8 h. The letters on the green line denote the changes in pressure made to purge ammonia gas. Accordingly, if the pressure difference between tanks A and B is known, the purge ratio from the discharge point in tank B can be calculated. If  $(P_A - P_B) = \Delta P = 0.014\text{ atm}$ , according to Fig. 4, the nitrogen gas concentration can be 13 % when the ammonia gas concentration in tank is 87 %. Then, the nitrogen purge rate is [12, 13]

$$P \times V = n \times R \times T,$$

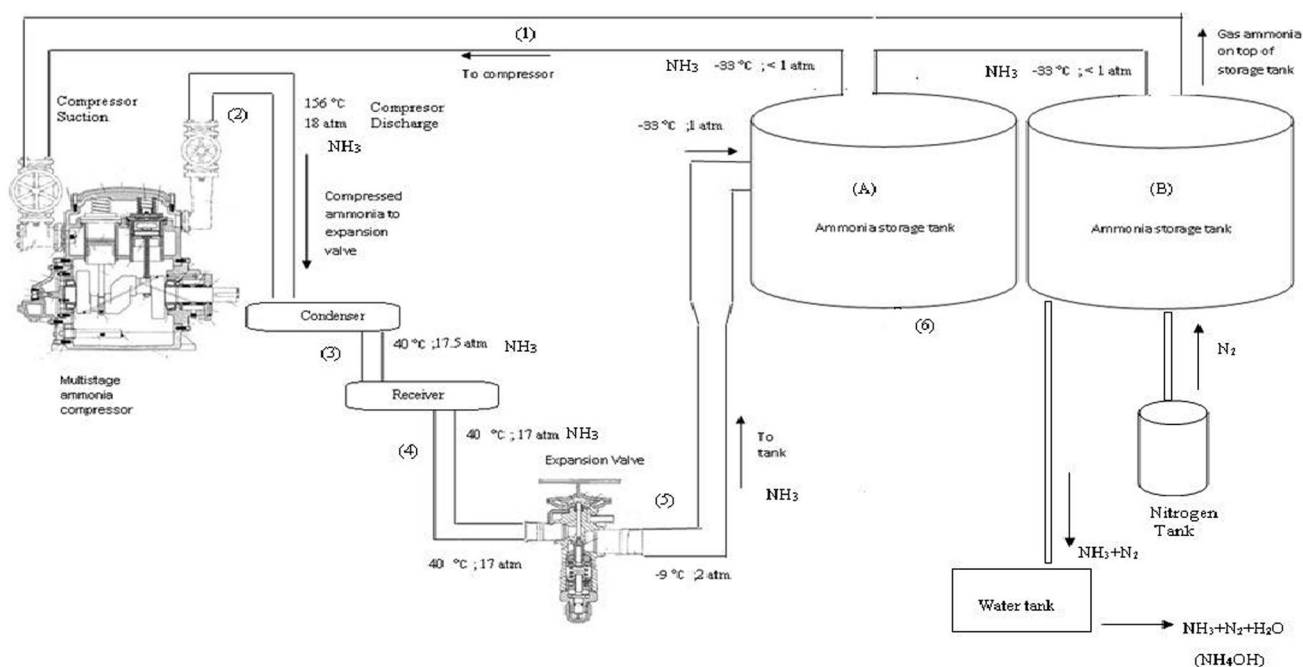
$$P_A = 0.048\text{ atm}, P_B = 0.034\text{ atm},$$

$$(P_A - P_B) = \Delta P = 0.014\text{ atm},$$

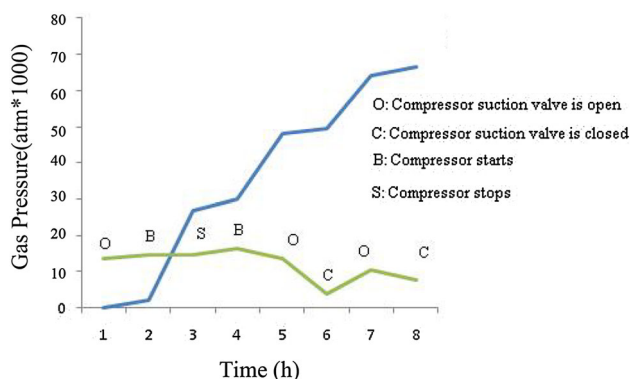
$$V = \text{Volume of the ammonia storage tank in the process} \\ : 23,000\text{ m}^3,$$

$$V = 23,000\text{ m}^3 \times \left(\frac{13}{100}\right) = 2990\text{ m}^3 \times 1000\text{ dm}^3 \\ = 2,990,000\text{ dm}^3,$$





**Fig. 1** Schematic representation of purging achieved using nitrogen during ammonia storage



**Fig. 2** Operational directions against time and pressure in tanks. The Y-axis shows the ammonia and nitrogen pressures; the X-axis expresses the time period of 8 h. The green line represents the pressure change with ammonia gas concentration during 8 h, and the blue line shows the pressure change of nitrogen gas during the purging process for 8 h. The letters on the green line show the changes made to purge ammonia gas

$$R = 0.082 \left( \frac{\text{atm} \times \text{dm}^3}{\text{mol} \times \text{K}} \right),$$

$$T = 20 \text{ } ^\circ\text{C} \text{ (Temperature in tank B),}$$

$$P \times V = n \times R \times T,$$

$$\begin{aligned} 0.014 \times 2,990,000 &= n \times 0.082 \times 293 \\ &= 1804.5 \text{ (mol h}^{-1}\text{)} \times 28 \text{ (g mol}^{-1}\text{)} \\ &\quad \times (1 \text{ cm}^3/0.001251 \text{ g)} \\ &= 38,995 \text{ dm}^3 \text{ h}^{-1}. \end{aligned}$$

If  $P$  increases ( $P_A \gg P_B$ ), because of the pressure difference, the ammonia concentration in the empty tank B may increase.

Ammonia gas is transferred from tank A to tank B by the compressor suction lines. When the operation is complete and once the ammonia concentration is 100 %, the pressure difference between the two tanks,  $P$ , will be the lowest. Then, the ammonia concentration can be changed depending on pressure, as per the expression below [14]:

$$P \times V = n \times R \times T,$$

$$P = \left( \frac{n}{V} \right) \times R \times T.$$

By assuming inter-dependence between the variables concentration and pressure, the following correlation equation can be obtained [14]:

$$dP = dC \times R \times T,$$

$$P = C \times R \times T.$$

The temperature in the empty tank is thought to be equivalent to the air temperature because of the atmospheric pressure conditions maintained in the tank. Pressure ( $P$ , atm) and concentration ( $C$ , mol dm<sup>-3</sup>) are the two variable parameters that must be considered in this equation.

If the pressures in tanks A and B are  $P_A = 0.053$  atm and  $P_B = 0.046$  atm, respectively, for increasing the pressure and ammonia concentration in tank B, the compressor suction valve in this tank is opened. However, the



compressor does not start working. Vaporized ammonia from tank A flows into tank B because of the concentration difference, and thus, the ammonia gas pressure in tank B increases. When the ammonia gas pressure in tank A increases, the compressor begins to work; hence, the gas pressure in tank A is ensured to decrease. During this period, the compressor is running, and the compressor suction on tank B side is closed in order to prevent the flow of ammonia gas from tank B to the compressor suction line. When the pressure in tank A decreases to 0.043 atm, the compressor is stopped, and the opening compressor suction on tank B side is opened to ensure that ammonia gas flows to tank B.

It is noteworthy that the ammonia gas pressure in tank B increases when ammonia flows into the tank after the compressor suction valve on tank B side is opened. During the ammonia gas transfer from tank A to tank B, nitrogen gas is discharged from the ammonia discharge point at the bottom of tank B. This nitrogen gas results from the purging using nitrogen in tank B. In this manner, a large pressure increase in tank B is prevented by discharging nitrogen gas.

In the present operation, the amount of purged nitrogen gas must be calculated. This purged nitrogen gas is absorbed by water and will minimize the ammonia content in the nitrogen/ammonia gas mixture. Thus, precipitation of ammonia as ammonium hydroxide is an eco-friendly approach.

Another purpose of the operation is to ensure that the entire amount of ammonia is used to exert pressure on the nitrogen gas, for purging nitrogen in tank B. The entire amount of ammonia gas in the available system is transferred from tank A to tank B. The vaporized part of liquid ammonia in tank A is sent to the multistage compressor for liquefaction, and this liquefied ammonia is sent to tank A for storage. Most of the vaporized ammonia in tank A flows to tank B because of the concentration gradient and the difference between B and C.

In this manner, ammonia gas is sent to tank B, compressed, and made to discharge nitrogen into the atmosphere. According to the values of the operational parameters shown in Fig. 2, because of the increasing pressure difference between tanks A and B caused by the compressor in function, vaporized ammonia gas flows from tank A to tank B, which has lower ammonia gas pressure. Because of the low concentration of ammonia, the gas flows to tank B via the compressor suction valve, without flowing into the compressor (Fig. 1).

The ammonia gas entering tank B forces the nitrogen gas in this tank to be expelled from the discharge point. Similarly, when the pressure difference between tanks A and B decreases, the compressor suction valve is closed and the compressor is allowed to run for allowing nitrogen

gas to flow between the tanks and for discharging nitrogen gas by creating pressure in the tank. Thus, the vaporized ammonia in tank A is liquefied and stored in tank A. Once the pressure of ammonia gas in the tank is increased by the multistage compressor, the compressor stops, and thus, liquid ammonia in tank A is vaporized.

Depending on the increase in the pressure of ammonia gas in tank A, the compressor suction valve of tank B opens, and thus, the entire amount of ammonia gas enters tank B from tank A. When the compressor suction valve is open, the compressor does not run, because the ammonia gas, which is vaporized in tank A and passed to tank B, can decrease the ammonia gas concentration in tank B. The main principle in this process is the increase in the ammonia concentration in tank B.

One way for this increase is as follows: The ammonia gas is vaporized in tank A, but in the meantime, the ammonia gas pressure in tank A must be increased extensively within a short process time. This operation will continue until the ammonia gas concentration in tank B is 100 %. When the ammonia gas concentration is 100 %, liquid ammonia can enter tank B. Moreover, in the time frame shown in Fig. 2, the ammonia gas concentration is monitored in tank B, and accordingly, the amount of purged nitrogen gas is calculated.

The data in Fig. 2 show the gasification ability of ammonia with time and can be used to obtain important information on the compressor efficiency.

When the concentration of ammonia gas is 100 %, the compressor suction valve in tank B and the liquid ammonia entry line of the compressor to tank B are opened.

### Destruction and exergy analysis for the nitrogen cycle during purging

Exergy analysis is carried out to optimize the operational and geometrical parameters of the ammonia pump and ammonia storage tank in the nitrogen cycle of the limiting ammonia concentration system. This analysis facilitates assessment of the combined effect of heat transfer and pressure drop through simultaneous interactions with the pump. However, the pressure drop in the ammonia pump and tank affects exergy losses. Thus, exergy analysis for the nitrogen cycle of the limiting ammonia concentration system is necessary.

The operating parameters for the compression system are listed in Table 1.

For the ammonia pump component, the exergy losses are evaluated from the exergy balance. The exergy is defined by [15]:

$$e = T_a(s_{\text{out}} - s_{\text{in}}).$$



**Table 1** Operating parameters of the ammonia compression system

Parameters	Compression mode
$T_a$ (K)	308
$T_{cd}$ (K)	313
$T_{exp}$ (K)	278
$T_{cp}$ (K)	278
$T_{pump}$ (K)	283
$T_{vessel}$ (K)	293

Using the exergy analysis method, the exergy losses occurring in all five components of the compression cycle (Fig. 1) are calculated as follows:

The exergy loss in the multistage compressor is:

$$e_{cp} = T_{cp}(s_2 - s_1).$$

The exergy loss in the condenser is:  $e_{cd} = T_{cd}(s_3 - s_2)$ .

The exergy loss in the expansion valve is:

$$e_{exp} = T_{exp}(s_5 - s_4).$$

The exergy loss in the ammonia pump is:

$$e_{pump} = T_{pump}(s_7 - s_6).$$

The exergy loss in the vessel is:  $e_{vessel} = T_{vessel}(s_1 - s_6)$ .

The total exergy loss in the compression cycle is:

$$e = e_{cp} + e_{cd} + e_{exp} + e_{pump} + e_{vessel}.$$

The exergy efficiency of the compression system is:

$$\% \eta = 1 - (e/w).$$

The exergy analysis results of the ammonia compression system with operating modes are listed in Table 2.

### Chemical exergy analysis of purging system

When nitrogen purging is performed, nitrogen gas and ammonia gas are discharged to the waste water tank. During this time, ammonium hydroxide is formed by the reaction between water and ammonia. The chemical exergy equation for this reaction is:

$$\psi_r = v_i g_{f,i},$$

**Table 2** Exergy analysis results of the ammonia compression system

Parameters	Ammonia compression mode
$w$ (kJ kg <sup>-1</sup> )	41.258
$e_{cp}$ (kJ kg <sup>-1</sup> )	9.251
$e_{cd}$ (kJ kg <sup>-1</sup> )	4.442
$e_{exp}$ (kJ kg <sup>-1</sup> )	2.369
$e_{pump}$ (kJ kg <sup>-1</sup> )	2.254
$e_{vessel}$ (kJ kg <sup>-1</sup> )	5.124
$e$ (kJ kg <sup>-1</sup> )	23.44
(%) $\eta = 1 - \frac{e}{w}$	43.18

where  $\psi_r$  is the molar exergy of the synthesis reaction at 1 atm and 25 °C [16].

For the purging process, the chemical exergy is determined using the molar exergy values for ammonia and water.

$$\psi_{NH_4OH} = g_{f,NH_3} + g_{f,H_2O}$$

The exergy for ammonium hydroxide formation from ammonia and water [16] is:

$$g_{f,NH_3} = 327.4 \text{ kJ mol}^{-1}, \quad g_{f,H_2O} = 1.3 \text{ kJ mol}^{-1},$$

$$\psi_{NH_4OH} = 328.7 \text{ kJ mol}^{-1}.$$

### Results and discussion

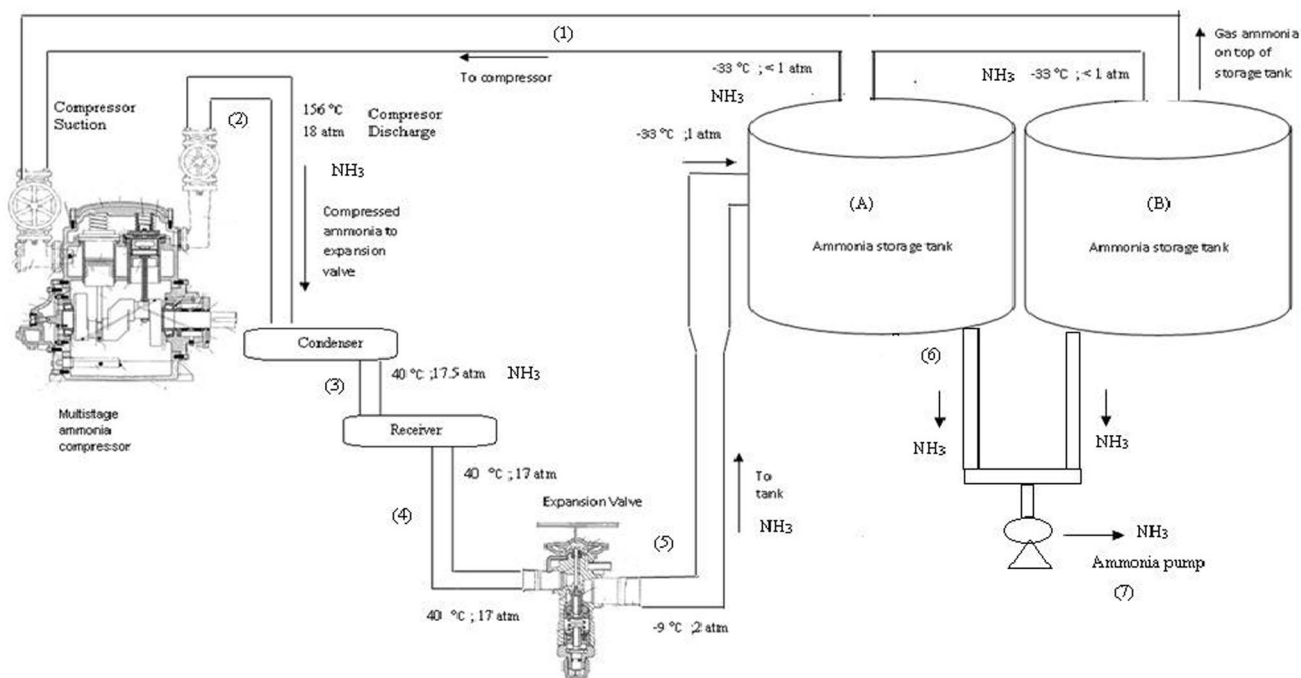
Purging of refrigerated materials such as ammonia requires special conditions for storage and necessitates the use of some special processes. The residual ammonia in the system after purging with nitrogen is released into the environment. Our process helps in mitigating the environmental hazards caused by ammonia. In this study, a mixture of ammonia and nitrogen, which is present in an empty tank made inert by using nitrogen, is used to discuss how the empty tank purged by ammonia is filled by liquid ammonia. During purging of nitrogen from the tank, environmental factors must be considered, despite the low concentration of ammonia (<10 %) resulting from the small amount of ammonia purged.

In the abovementioned process, each storage tank has a compressor suction line and a valve, and a liquid ammonia entry point for the compressor discharge line. According to the process conditions, this system can have liquid ammonia pumps and a gas return line to the tank (Fig. 3). Before liquid ammonia is taken to the empty tank, ammonia gas should be filled in the tank because ammonia is a refrigerated liquid, and hence, liquid ammonia conditions should be maintained in the tank (1 atm, -33 °C). On the other hand, before liquid ammonia is transferred to the empty storage tank, because of the process conditions, the ammonia gas concentration in the tank does not show a linear change. The change in the ammonia gas density with temperature is more active than the change in nitrogen gas density with temperature. Finally, with the increasing concentration of ammonia gas in the tank, a sudden increase in the nitrogen discharge rate is observed, which confirms the temperature–density correlation.

During purging of nitrogen gas in tank B, environmental factors should be considered, and dissolution in water would be the most economical solution to minimize environmental contamination by ammonia. Therefore, an eco-





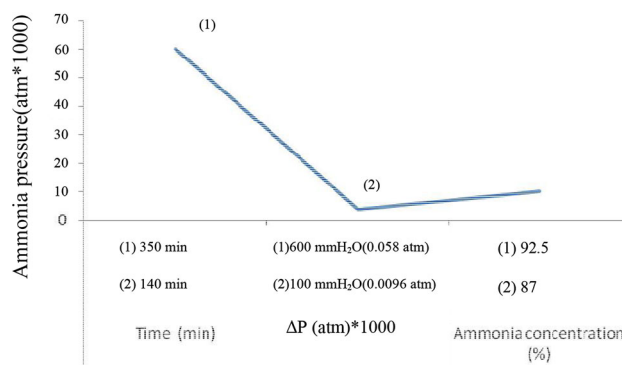


**Fig. 3** Operation of tank filled with liquid ammonia (vaporized ammonia from tank A to tank B goes to the compressor and is sent to the storage tank upon liquefaction by the compressor)

friendly method would be to precipitate ammonia as ammonium hydroxide.

Transfer of ammonia to tank B can be accomplished by various methods; however, the best option when using the present system will be to feed compressed and liquefied ammonia from the multistage compressor. In this method, because of the ammonia gas in the filled tank, the ammonia concentration in the empty tank is brought to 100 %, and then, some part of vaporized ammonia in the filled tank is compressed by the compressor; thus, liquefied ammonia is sent by the compressor discharge line to the filled tank. Exergy analysis performed for this method reveals that exergy losses for the present system result from losses in the ammonia tank and ammonia pumps.

According to Fig. 2, because of the pressure difference between tanks A and B, the ammonia gas in tank B forces the nitrogen gas in the tank to expel. Therefore, nitrogen gas can purge to the atmosphere from the discharge points in tank B. Another detail given in Fig. 4 is the nitrogen gas ratio for every pressure value of the nitrogen–ammonia mixture. According to Fig. 4, 350 min after the purging of ammonia gas, the pressure and concentration of the gas in tank B were measured as 600 mmH<sub>2</sub>O (~0.058 atm) and 92.5 %, respectively. Then, the purging operation continued for further 140 min, during which time the pressure in this tank was 100 mmH<sub>2</sub>O (~0.0096 atm) and the ammonia gas concentration was 87 %. The ammonia pressure in tank B showed a large alteration after the second measurement. In



**Fig. 4** Ammonia concentration purged due to pressure difference (for tank B)

large-volume industrial ammonia storage systems (23,000 m<sup>3</sup>), the uncompressed ammonia gas from the compressor line and leakages in other processes can induce slight differences in the pressure values measured during the purging operation. We expect the ammonia gas pressure to decrease in this process because we attempt to decrease the ammonia gas concentration. However, if the process is not isolated on the industrial scale, a sharp increase in ammonia gas pressure can occur when the compressor is started or in the event of any leakage. As illustrated in Fig. 2, after 6–7 h of operation, the ammonia gas concentration can increase; this is because when the compressor suction valve is first closed (C) and then opened (O), gasified ammonia cannot be



discharged from the system, which results in increased ammonia gas pressure. However, when the compressor is started, it imparts a driving force to expel ammonia gas from the discharge points, thereby causing a decrease in the gas pressure.

With this ratio and the pressure difference between tanks A and B, the amount of nitrogen purged in tank B (Fig. 1) can be determined, and exergy analysis can be performed. Related data are given as nitrogen concentration in the nitrogen–ammonia gas mixture as a function of pressure and time. The aim here is to calculate the discharge rate of purged nitrogen in the mixture.

The measurement data for the ammonia storage vessel are acquired by an ammonia manometer pressure gauge with a measurement range 0–60'' H<sub>2</sub>O (accuracy 1.0 %, glycerin fillable).

The studies discussed here, in particular for industries, in which corrosive and cryogenic materials are used, explain how to remove corrosive materials, like ammonia, by purging the lines during periodic maintenance work. According to these studies, gas purging is most commonly used in industries that apply thermodynamic cycles, like petroleum refineries and energy production facilities.

The purpose of this study was to clean ammonia gas from an ammonia storage system and to purge the ammonia in an optimal way. The cheapest, detected method was the absorption of ammonia purged into water. Because the formation of ammonium hydroxide via reaction between ammonia and water is inevitable, it will be purged optimally. This ensures that there is no damage to the flora when ammonium hydroxide is discharged into empty agricultural fields.

## Conclusions

In industrial processes, various problems related to environmental pollution and equipment corrosion are encountered during purging with corrosive liquids such as ammonia. For this reason, proper maintenance of storage systems is important. A possible, inexpensive solution to this problem is the use of multistage compressors, so that the storage system is conditioned by liquefaction; that is, using nitrogen gas for purging ammonia gas. Ammonia is precipitated as ammonium hydroxide at the end of the process, and hence, there is minimum environmental load.

In this study, the operational parameters for purging of ammonia pipelines and storage tanks before liquid ammonia was transferred into the tank, was investigated by using real-time process data. Further, an exergy analysis was performed and the purge rate of compressed nitrogen gas was calculated. It is proposed that ammonia

in the ammonia–nitrogen gas mixture is purged by precipitating ammonia as ammonium hydroxide, which is one of the most important results. According to the data obtained for the present system, the amount of purged nitrogen is 38,995 dm<sup>3</sup> h<sup>−1</sup>. In addition, exergy analysis of the present system was performed using the thermodynamic parameters, and the exergy loss was determined to be 43.18 %.

The present system handles a very large industrial volume of around 23,000 m<sup>3</sup>; hence, strict control of each system parameter is not easy. Therefore, the expected results were not obtained even after optimization of the process conditions. However, the proposed system is cost-effective and less time-consuming and it discharges relatively low amounts of environmental pollutants; thus, there are no notable concerns regarding the practical implementation of the system.

**Open Access** This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

## References

1. Shi LL, Meng LC, Nandong X (2005) Researches on the factors affecting ammonia-purge efficiency of landfill leachate in purging tower. *Ind Saf Dust Control* 6:12
2. Oberski C, Cavataio G, Van Nieuwstadt MJ, Webb T, Ruona W (2010) U.S. Patent No. 7,770,384. U.S. Patent and Trademark Office, Washington, DC
3. Ishizaka T, Gunji I, Kannan H, Sawada I, Kojima Y (2003) U.S. Patent Application No. 10/516,311
4. Shaikh F, Lawrence D, Cooper S, Castleberry L Jr (2014) U.S. Patent No. 8,621,848. U.S. Patent and Trademark Office, Washington, DC
5. Sun J, Mupparapu S, Tarabulski TJ, Park PW (2013) U.S. Patent No. 8,459,012. U.S. Patent and Trademark Office, Washington, DC
6. Mayer F, Hornung M, Bürgi L, Gerner P (2014) U.S. Patent No. 8,771,598. U.S. Patent and Trademark Office, Washington, DC
7. Le Lostec B, Galanis N, Millette J (2012) Experimental study of an ammonia-water absorption chiller. *Int J Refrig* 35(8): 2275–2286
8. Wright CJ (2015) U.S. Patent No. 9,150,139. U.S. Patent and Trademark Office, Washington, DC
9. Ma D, Zhang Z, Li Y (2015) Investigation of gas purging process in pipeline by numerical method. *Process Saf Environ Prot* 94:274–284
10. Maekawa K (2010) U.S. Patent No. 7,691,208. U.S. Patent and Trademark Office, Washington, DC
11. Dincer I, Kanoglu M (2011) Refrigeration systems and applications, 2nd edn. Wiley, New York
12. Çengel YA, Boles M (1989) Thermodynamics: an engineering approach, 5th edn. McGraw-Hill, New York
13. Hogan JD (ed) (1996) Specialty gas analysis: a practical guidebook. Wiley



14. Maalouf S, Boulawzksayer E, Clodic D (2012) Orc finned—tube evaporator design and system performance optimization. In: International refrigeration and air conditioning conference, Purdue, US
15. Querol E, Borja G-R, Perez-Benedito JL (2013) Exergy concept and determination, practical approach to exergy and thermoeconomic analyses of industrial processes. Springer, London
16. Wall G (1998) Exergetics. Mölndal, Sweden. <http://exergy.se>

